Extension of Compaction Bands in Porous Sandstones

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Collaborators

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- Kurt Sternlof (Stanford)
- Dave Pollard (Stanford)

Support: U.S. Dept of Energy,
Office of Basic Energy Sciences

What do compaction bands look like in the field?

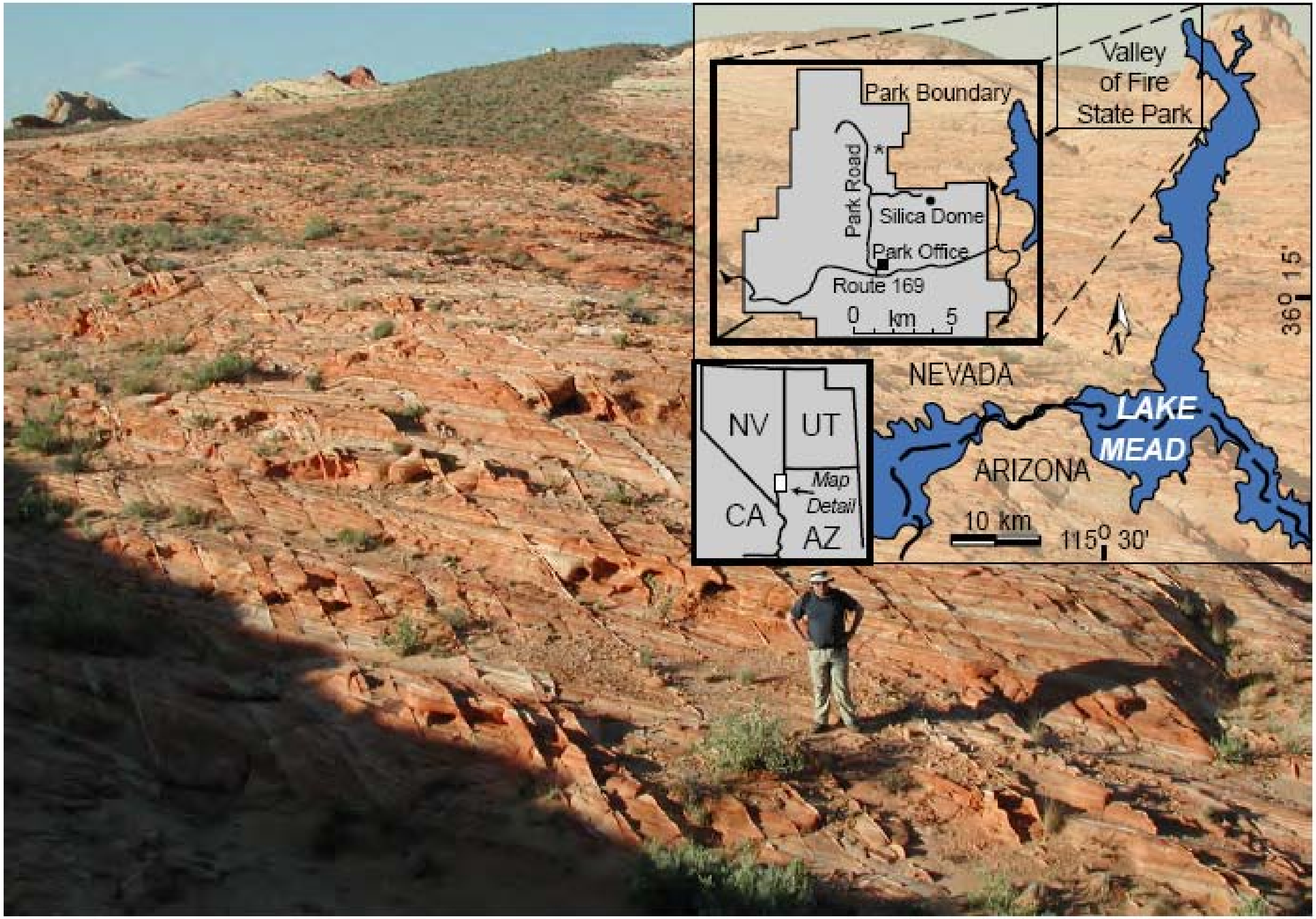


Figure 1. Location of the Valley of Fire State Park, southeastern Nevada (inset), where more than 20 square kilometers of the 1,400-m-thick eolian Jurassic Aztec Sandtone are extensively exposed. Photo shows view northward from the location marked * on the park detail. Throughout the upper half of the Aztec, compaction bands crop out in positive relief as sub-parallel, centimeter-thick, north-northwest-trending, steeply east-dipping tabular fins spaced from centimeters to meters apart.

From Sternlof, Rudnicki and Pollard, JGR, 2005

Compaction Bands: Earliest Structural Fabric of the Aztec

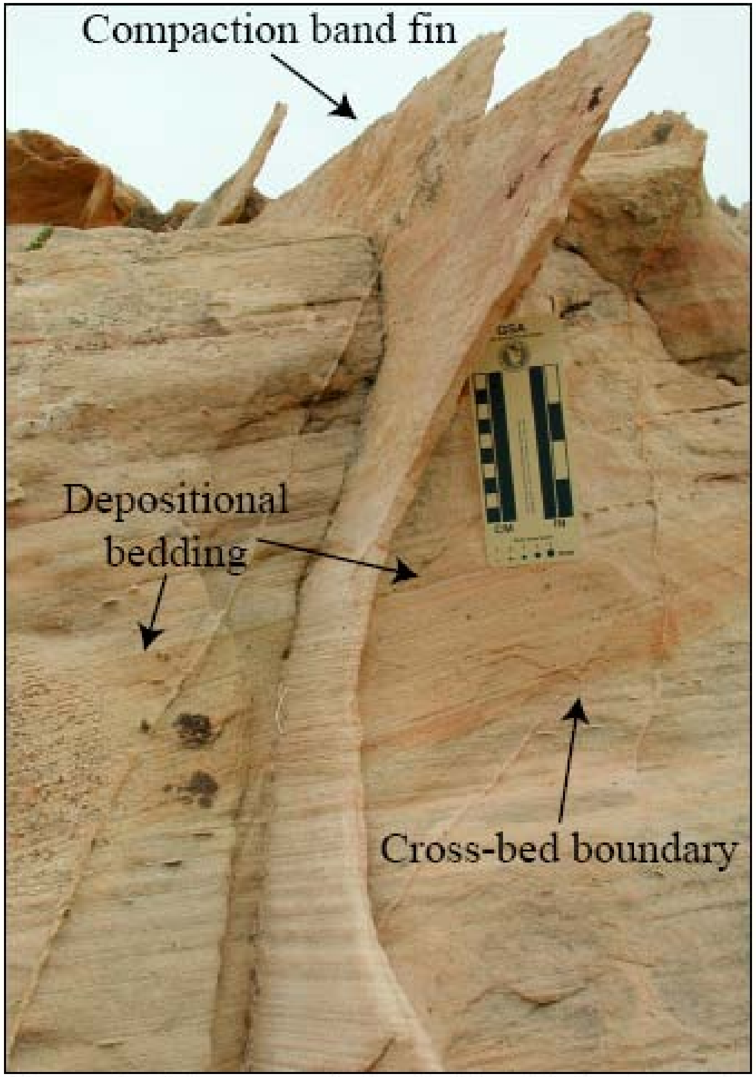


Figure 3. Close-up of a typical, well-developed compaction band fin in outcrop. Note that depositional bedding extends relatively undisturbed across the band, and is clearly visible on the fin.

Characteristic Compaction Band Arrays

Parallel

Cross-hatch

Anastomosing

in the Aztec Sandstone

From Kurt Sternlof, Stanford

Figure 2. Left-hand photo shows an outcrop of widely spaced, relatively planar and parallel compaction bands along the northeast flank of Silica Dome. Arrows indicate opposite tips of a single band 62 m long and up to 15 mm thick (illusory gaps in band continuity are due to outcrop topography and breaks in the telltale fin). A total of 16 tip-to-tip thickness profiles were measured using a steel tape and calipers. Right-hand photo illustrates that, even when closely spaced, compaction bands in this locale tend to remain planar (arrow indicates tip).

From Sternlof, Rudnicki and Pollard, JGR, 2005

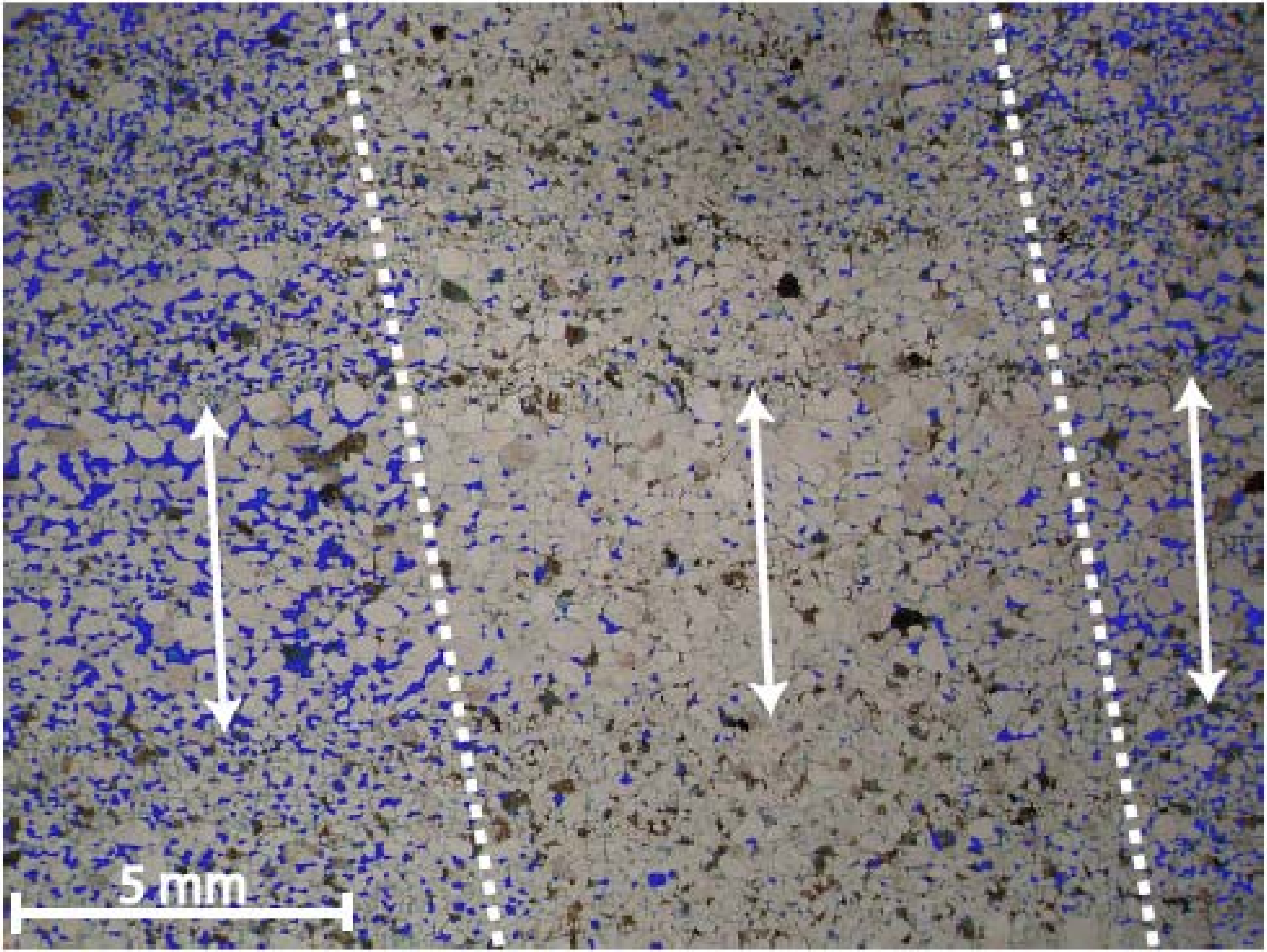


Figure 5. Photomicrograph of compaction band sampled 6.0 meters from the tip, where it is about 9 mm thick (dotted black lines). Blue indicates epoxy-filled pore space (~ 25% outside the band, ~ 10%

From Sternlof, Rudnicki and Pollard, JGR, 2005

Earth a solution to air pollution?

Scientists seriously consider injecting gases in ground

By Julie Deardorff
Tribune staff reporter

The plan to landfill air pollution might seem laughable.

As a stopgap solution to global warming, scientists have proposed capturing several billion tons of carbon dioxide from the air and injecting it deep into the earth for long-term storage.

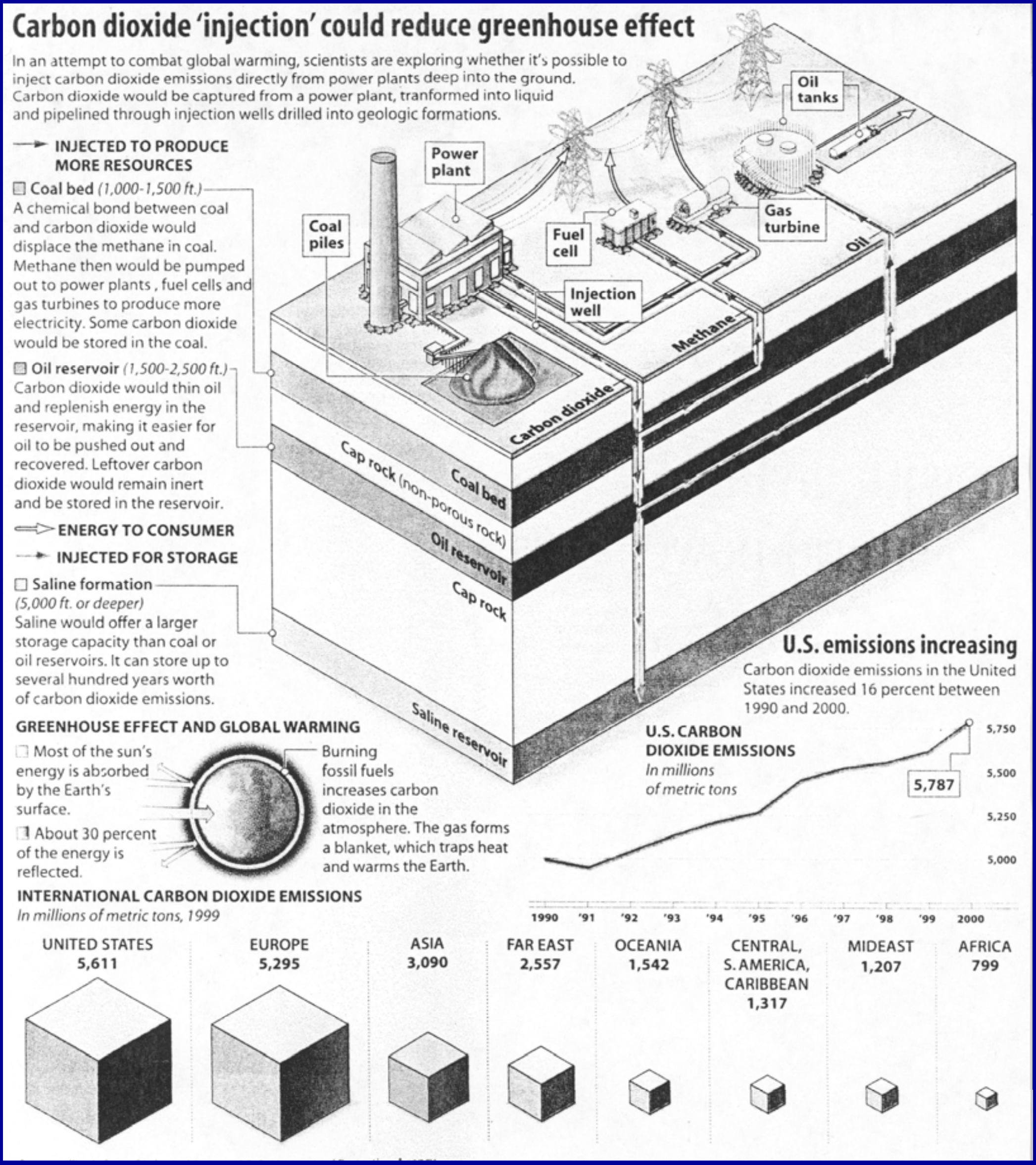
No one knows whether vast amounts of the greenhouse gas would stay put 2 miles below ground. Nevertheless, an increasing number of experts—including some environmentalists—believe the idea isn't as harebrained as it might sound.

With carbon dioxide emissions rising steadily in the U.S. and around the world, countries are casting about for ways to reduce the heat-trapping pollution. In the meantime, scientists say it can be unloaded into dark reaches of the earth, including saline aquifers, depleted oil wells, coal seams and the ocean.

The sprawling Illinois Basin, which extends into Indiana and western Kentucky, offers an ideal location to study three of the methods, say Illinois State Geological Survey officials. They are leading a multistate effort to bring up to $10 million in federal funding to the region to study and, perhaps, begin testing the technique.

Last month, the U.S. Department of Energy expanded funding to inspire state agencies, in-

PLEASE SEE **GASES**, BACK PAGE



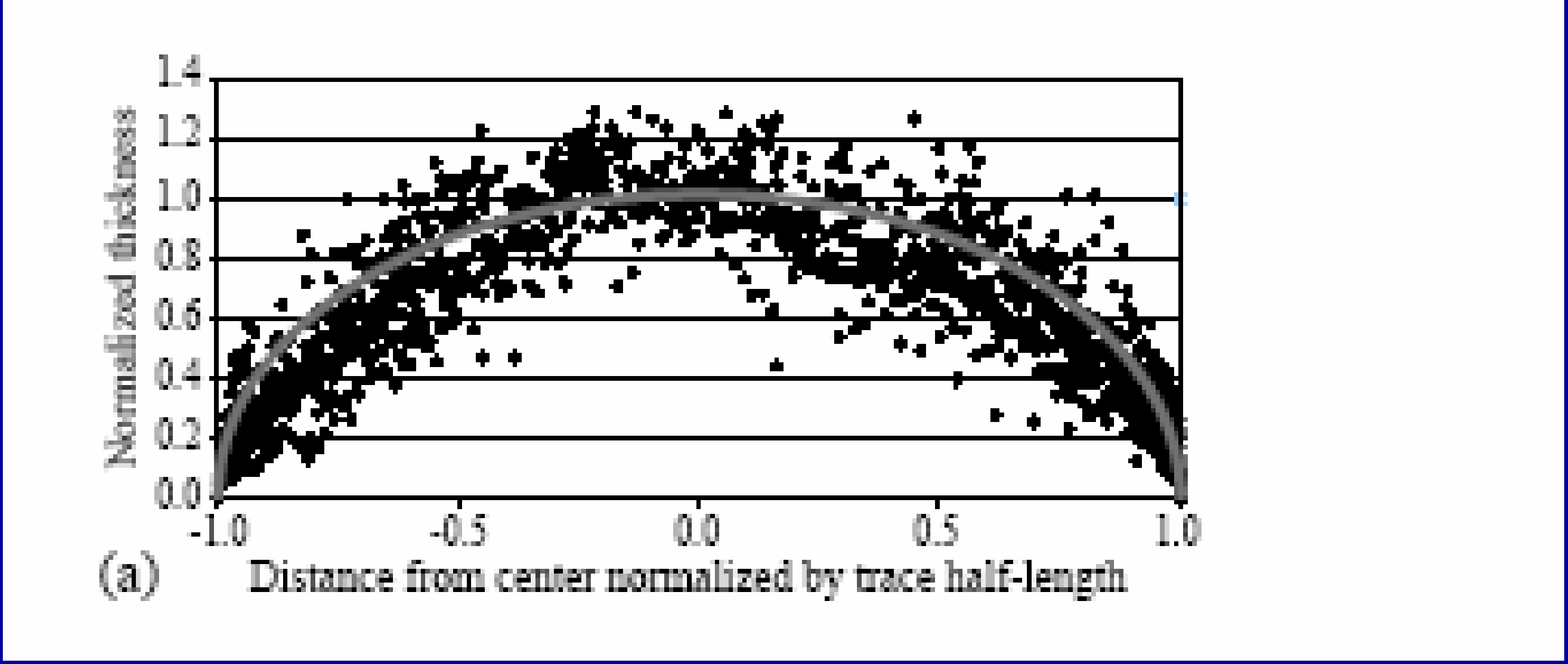
Chicago Tribune Front Page, January 27, 2003

In June, Ronald Oxburgh, Shell's chief in the United Kingdom called sequestration essentially the last best hope to combat climate change. "If we don't have sequestration, then I see very little hope for the world, Oxburgh told the British newspaper *The Guardian*."

Science, August 13, 2004.

Normalized band thickness vs. distance from center normalized by half-length.

From Sternlof, Rudnicki and Pollard (JGR, 2005) and Sternlof (PhD Thesis, 2006)

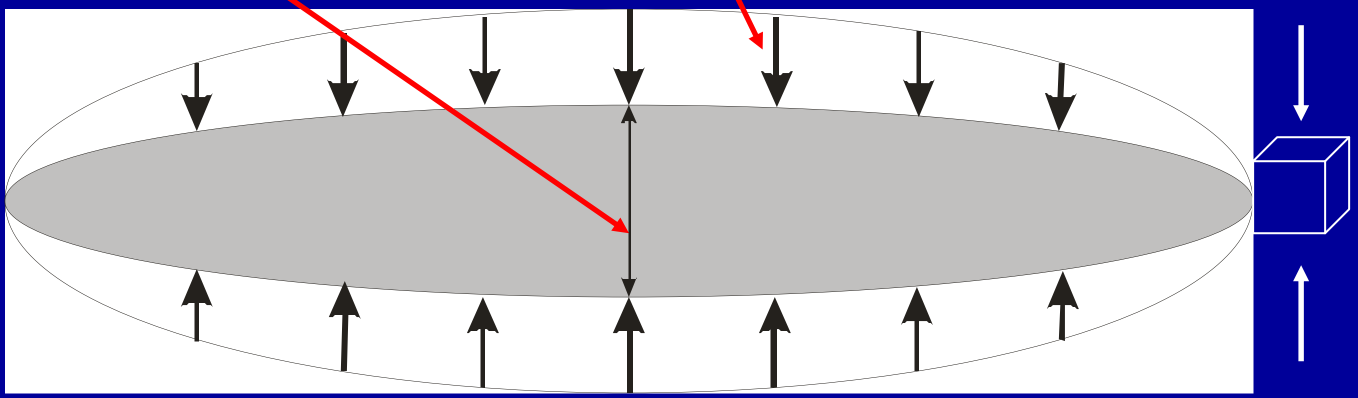


Ellipsoidal band with uniform inelastic compactive strain ε^p

$$\text{compactive displacment} = \frac{w\varepsilon^p}{1-\varepsilon^p} \approx w\varepsilon^p$$

$2w =$ band width

compressive stress ahead of the band is elevated sufficiently to cause compaction



Special (Relevant) Case

Uniaxial farfield strain: $\varepsilon_{11}^{\infty} = \varepsilon_{22}^{\infty} = 0$

$$\varepsilon_{33}^{\text{tip}} = \varepsilon_{33}^{\text{band}}$$

For very small aspect ratios

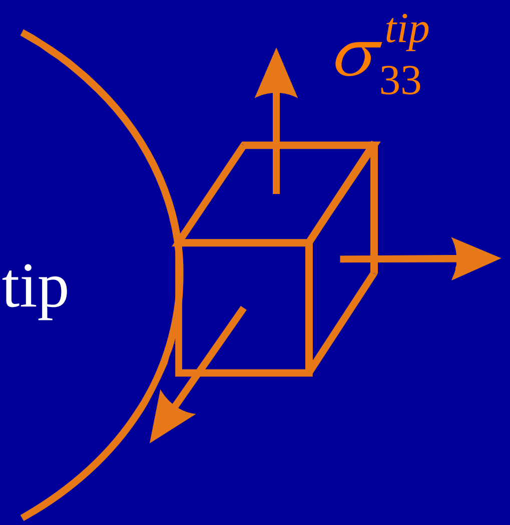
(: 10^{-3} to 10^{-4} from Sternlof data):

$\sigma_{33}^{\text{band}}\ ;\ \sigma_{33}^{\infty}$

$\varepsilon_{11}^{\infty} = \varepsilon_{22}^{\infty}\ ;\ 0$

and at tip:

band tip



$$\varepsilon_{33}^{\text{tip}} = \varepsilon_{33}^{\text{band}} \Rightarrow \sigma_{33}^{\text{tip}} = \sigma_{33}^{\text{band}} \frac{M_{\text{band}}}{M} + M\varepsilon_{33}^{p}$$

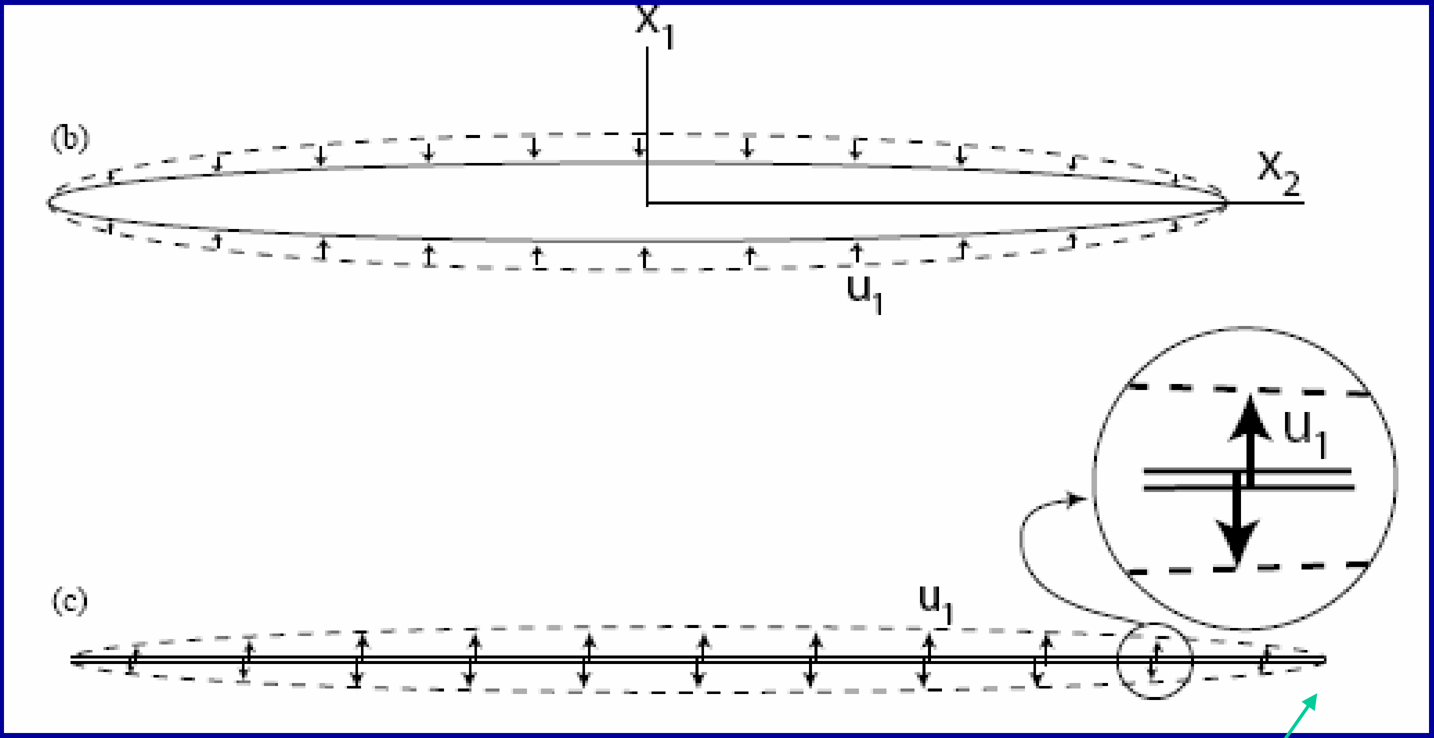
σ_{33}^{∞} : 40 MPa

$M = 2\mu(1-\nu)/(1-2\nu)$

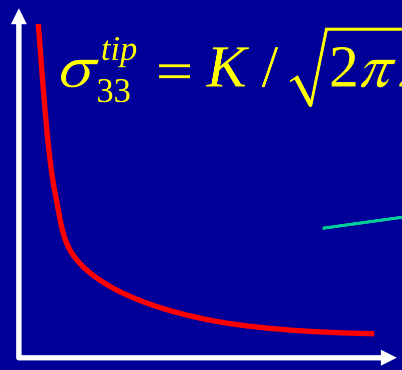
(isotropic elasticity)

$\approx$ 40 to 50 $\times\ \sigma_{33}^{\infty}$

“Anti-crack model” (Pollard, Fletcher, Sternlof)

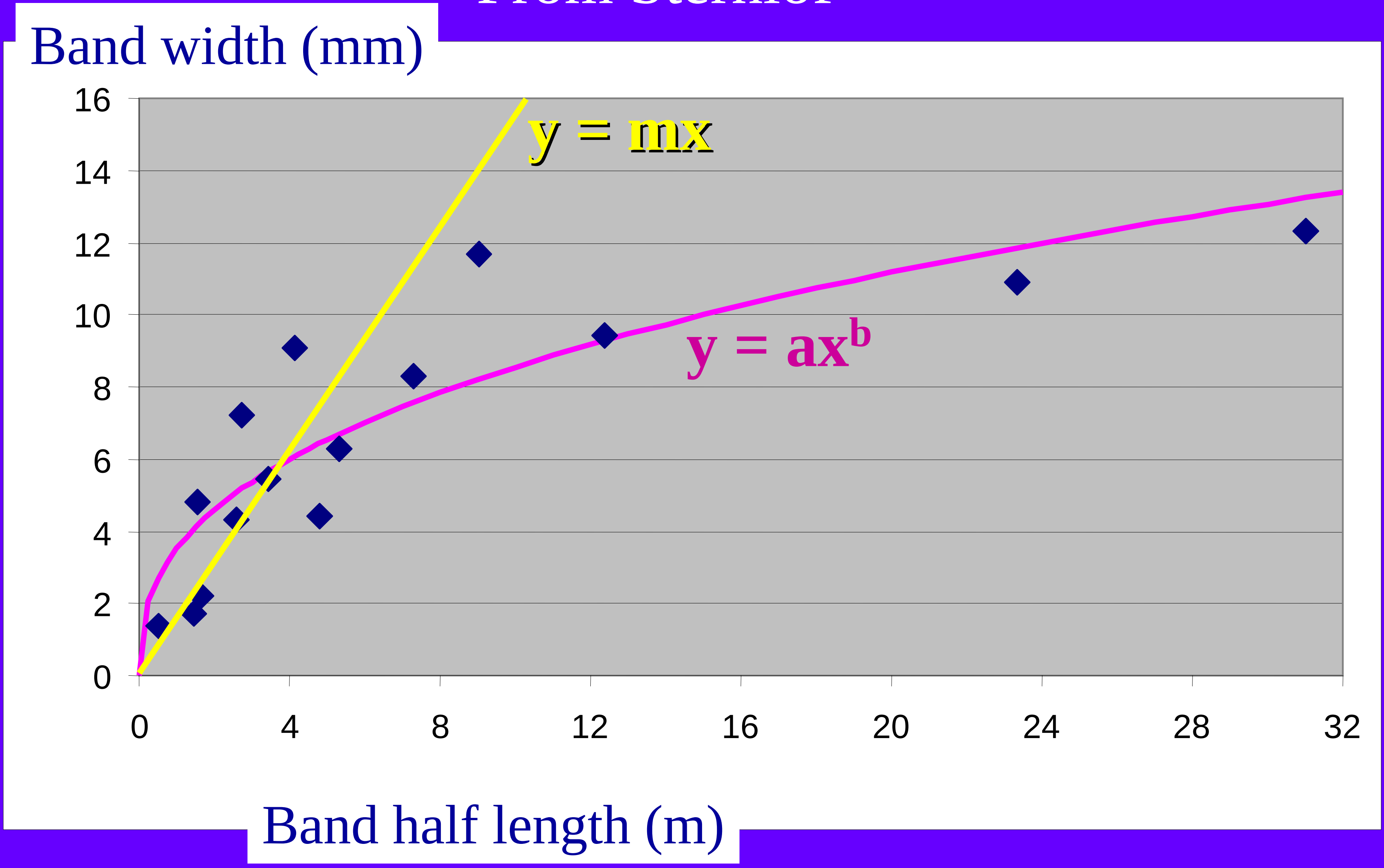


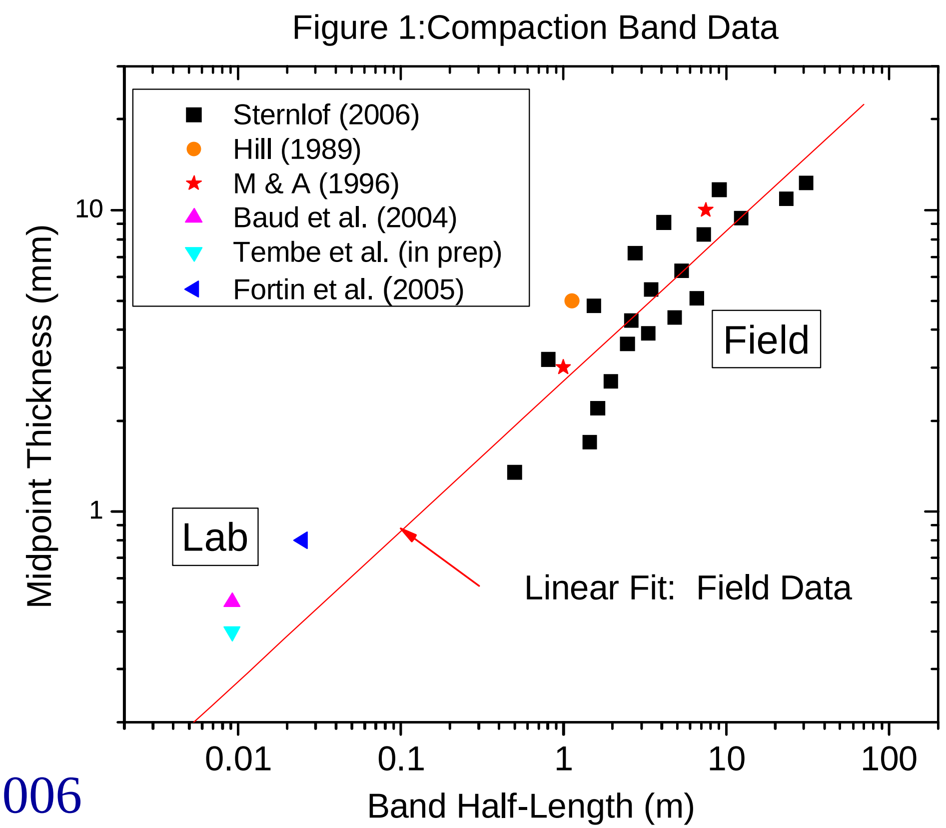
$$\sigma_{33}^{tip} = K / \sqrt{2\pi x_2}$$



Compaction Bands as Stiff Inclusions

From Sternlof



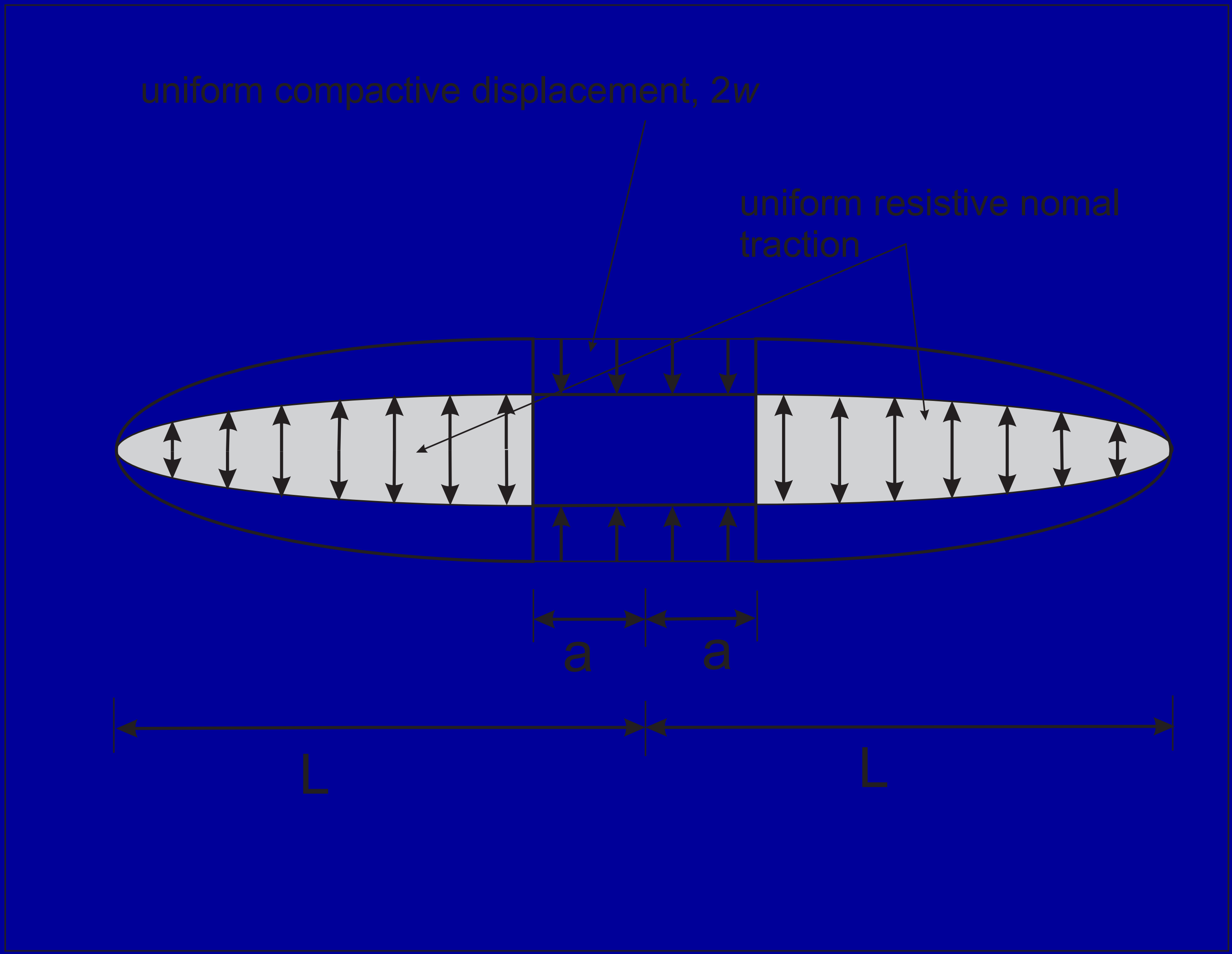


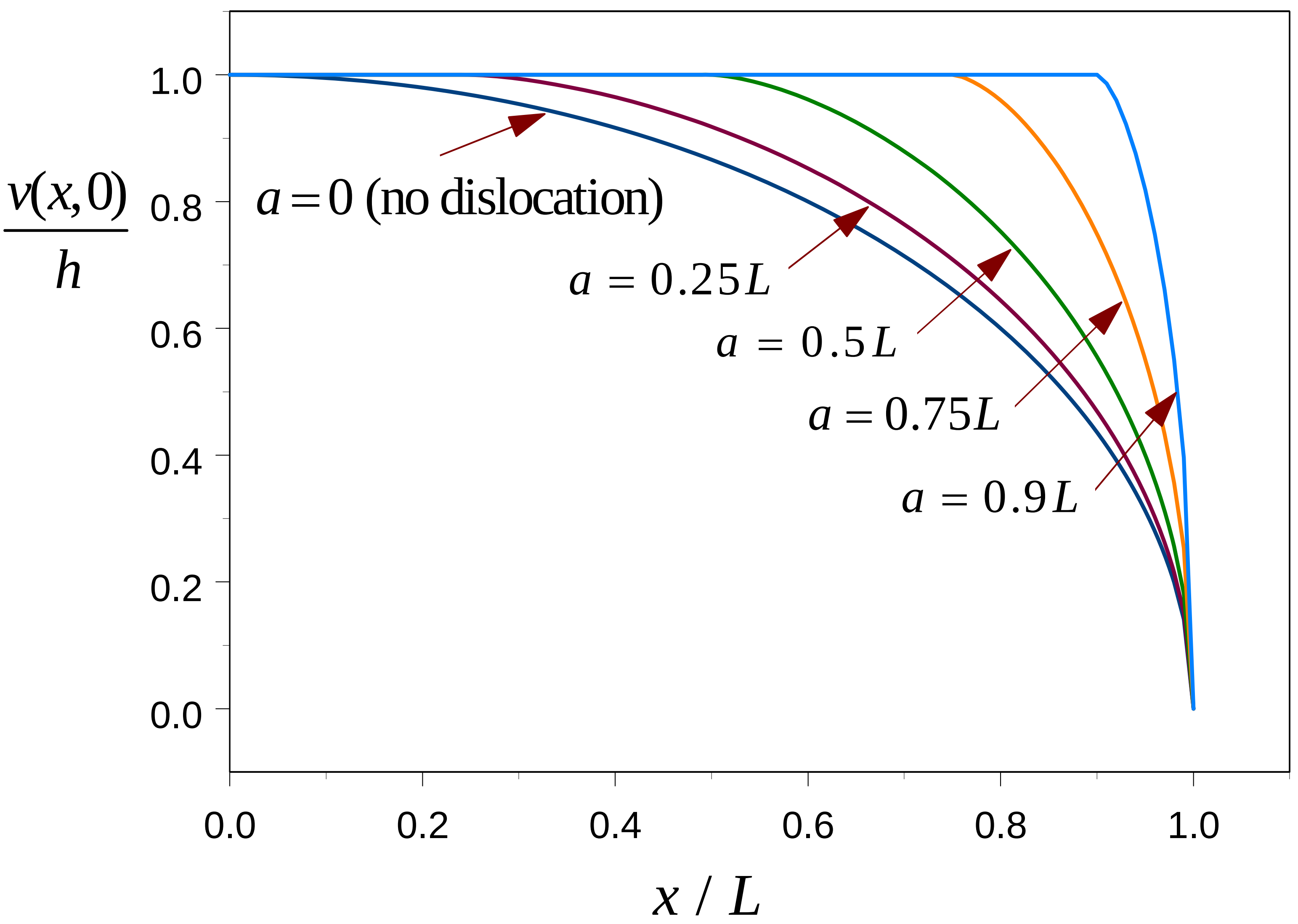
After Tembe, 2006

Linear Fit: $y = A + Bx$

	A	B
Field Data	0.43240	0.49891

Combined “anti-crack” and “anti-dislocation” model




$\frac{v(x,0)}{h}$
1.0
0.8
0.6
0.4
0.2
0.0
$a = 0$ (no dislocation)
$a = 0.25L$
$a = 0.5L$
$a = 0.75L$
$a = 0.9L$
0.0
0.2
0.4
0.6
0.8
1.0
x / L

$$K=\frac{\mu w}{(1-\nu)}\sqrt{\frac{\pi}{L-a}}\left[\underbrace{\frac{k\sqrt{L-a}}{E(k)-(1-k^2)K(k)}}_{F(k)}\right]$$

$$\text{where } k^2=1-(a/L)^2$$

$$F(k)=0.924 \text{ for } L=3a$$

$$F(k)=0.942 \text{ for } L=5a$$

$$G_{\text{crit}}=\frac{(1-\nu)}{2\mu}K_{\text{crit}}^2 \Rightarrow K_{\text{crit}}=\sqrt{\frac{2\mu G_{\text{crit}}}{(1-\nu)}}$$

$$\therefore 2w=\sqrt{L}\sqrt{\frac{8}{\pi}\frac{(1-\nu)G_{\text{crit}}}{\mu}}\underbrace{F(k)}_{\approx 1},\ L>>a$$

$$2w \approx \sqrt{L}\sqrt{\frac{8}{\pi}\frac{(1-\nu)G_{\text{crit}}}{\mu}},\ L >> a$$

For ν=0.2, $\mu = 8.333$ GPa,

Fit to $2w$ vs L data $\Rightarrow$ $G_{\text{crit}} = 30\ \text{kJ/m}^2$

From Sternlof and Rudnicki, GRL, 2005:

critical energy release rate

$$G_{crit} \approx \underbrace{h\xi\varepsilon^p}_{\text{net compaction}} \underbrace{M(\Delta/h)}_{\text{stress}=\sigma^+} + \mathrm{O}(\xi^2)$$

$\sigma^+ = 40$ MPa

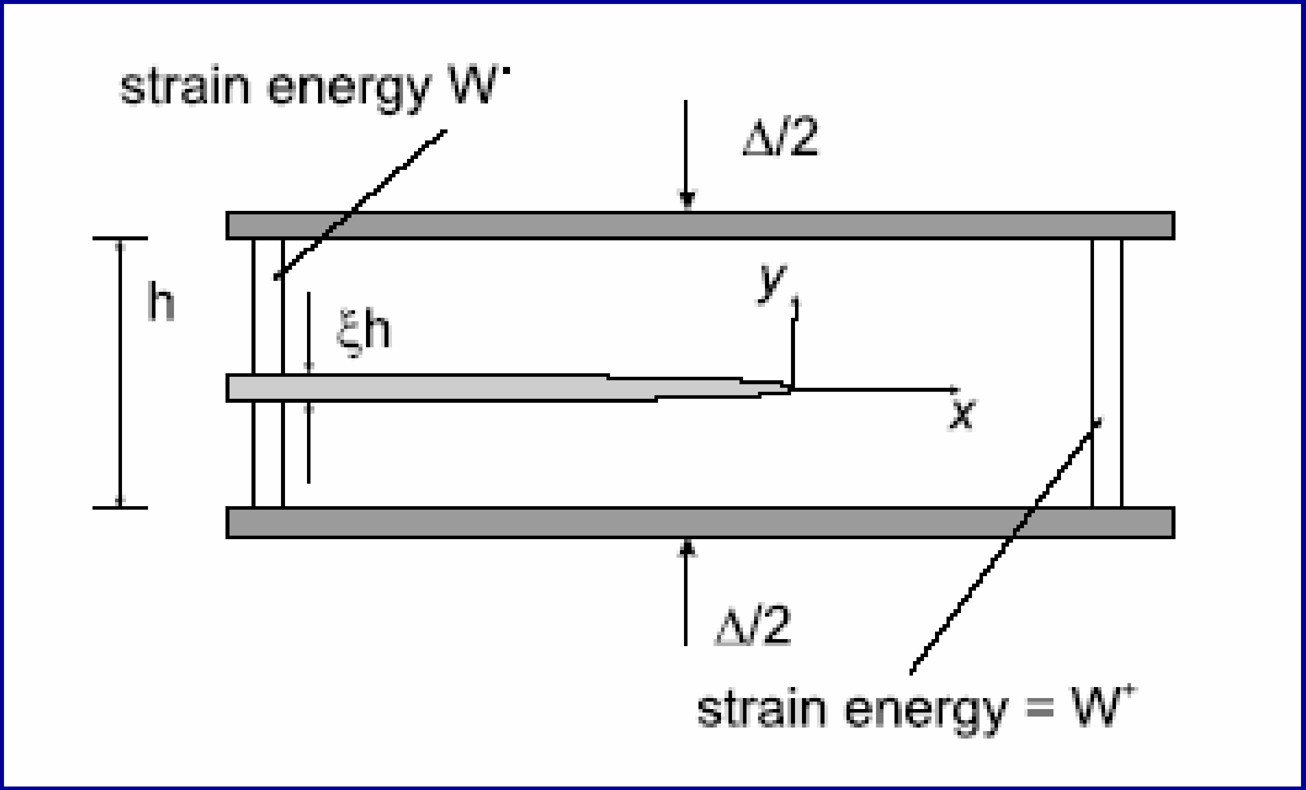
$h\xi = 0.01$ (1 cm thick CB, spaced 1 meter apart)

$\varepsilon^p = 0.1$ (corresponding to 10% porosity reduction)

$\Rightarrow$ $G = 40\ \text{kJ/m}^2$ (10 to 60 kJ/m^2 for range of stress estimates)

Energy Release Due to Compaction Band Propagation

Rudnicki and Sternlof, GRL, 2005 (after J. R. Rice, 1968)



energy release rate $G = W_{+} - W_{-}$

$$= \frac{1}{2}\frac{Mh}{(M/M_b)\xi + (1-\xi)}\left\{\left(\frac{\Delta}{h}\right)^2 \xi\left(\frac{M}{M_b} - 1\right) + 2\xi\varepsilon^p\left(\frac{\Delta}{h}\right) - \left(\xi\varepsilon^p\right)^2\right\}$$

Tembe et al., JGR, 2006 estimate "compaction energies" (equivalent to energy release rate) of 16 – 43 kJ/m^2 for Berea and Bentheim sandstones.

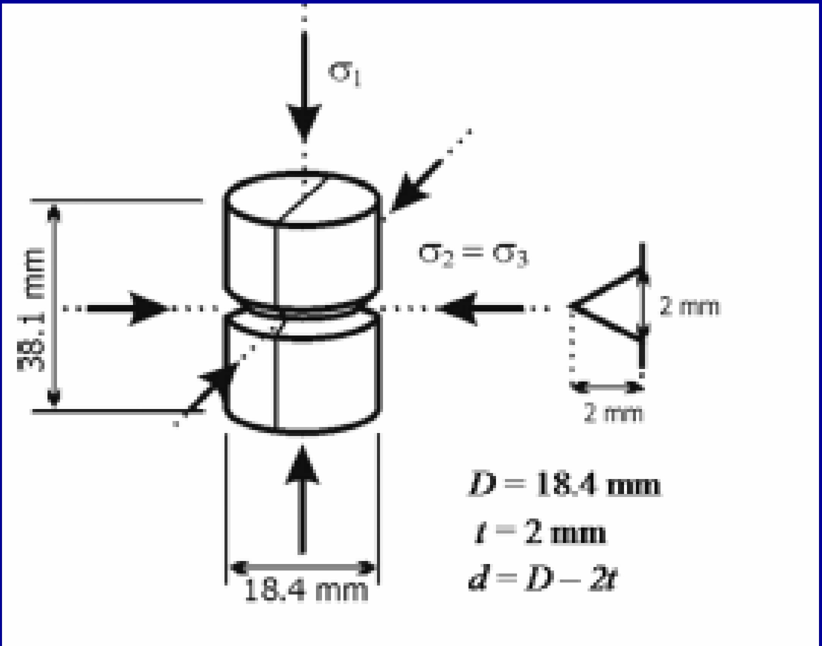
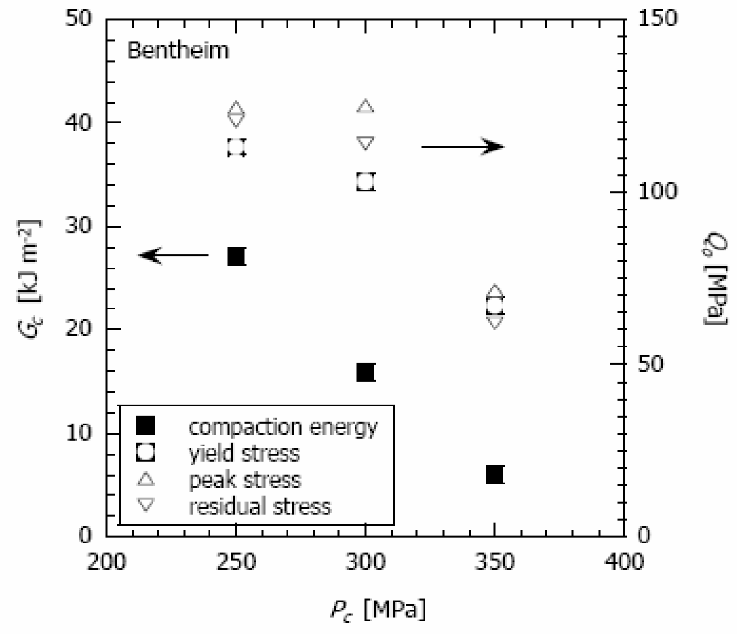


Figure 1. Geometric configuration of a notched sample loaded in a conventional triaxial apparatus.

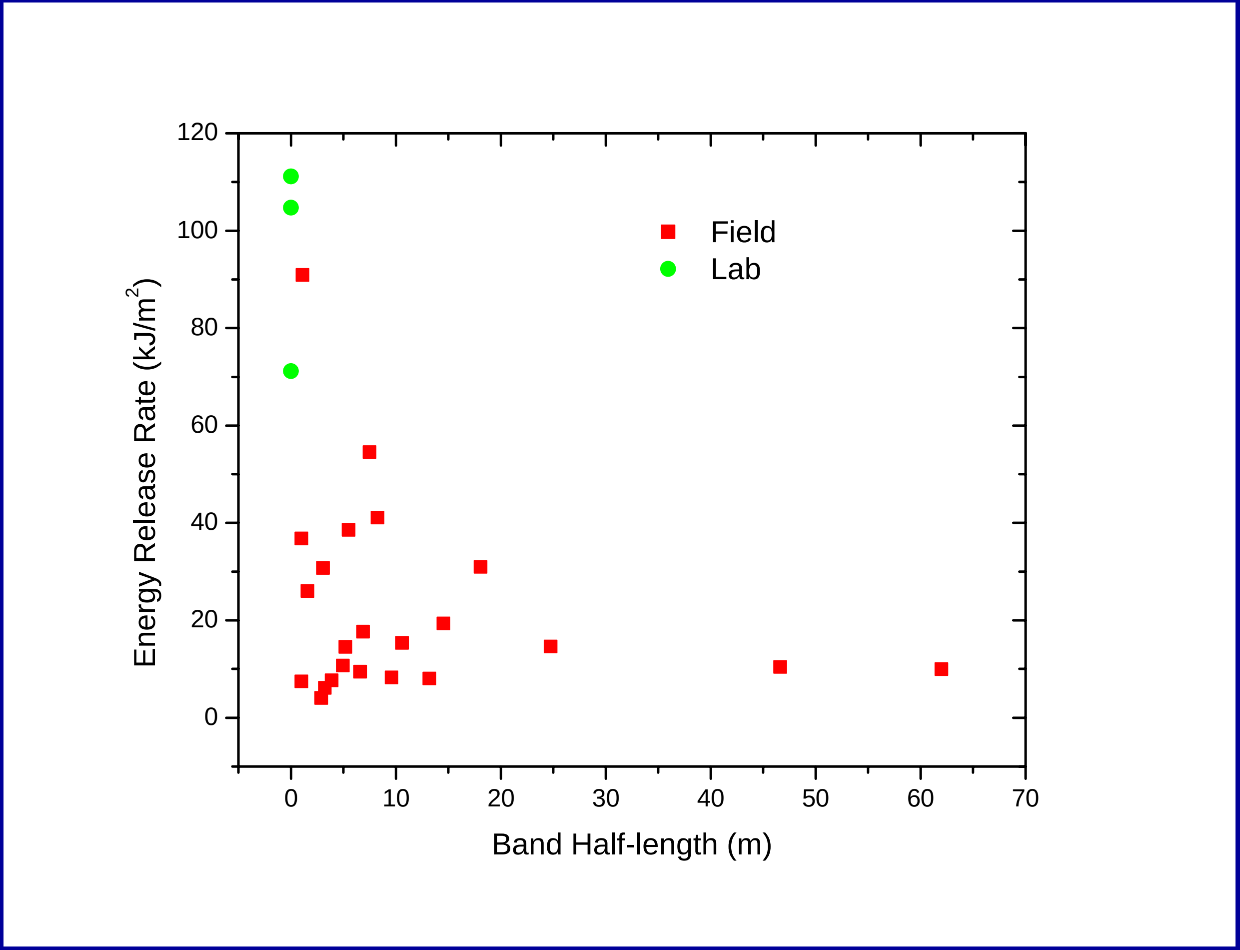


Energy release rate G_{crit} predicted from

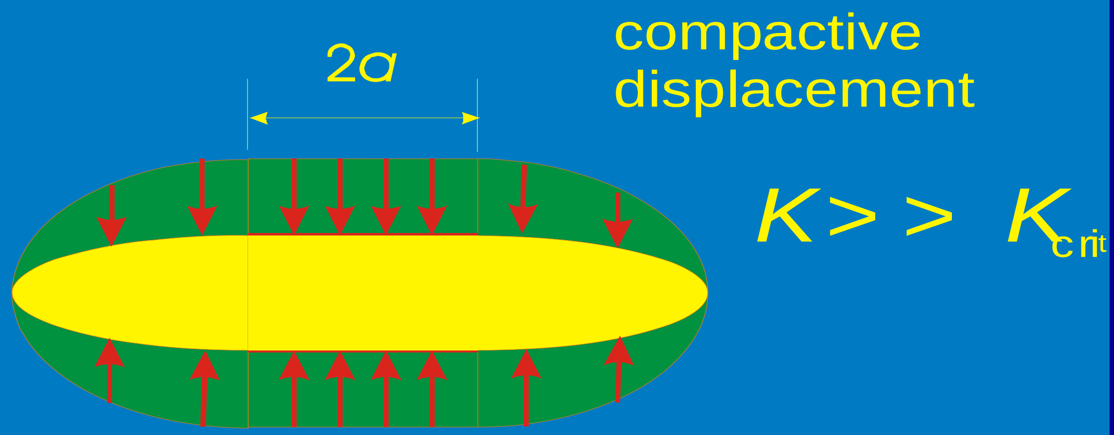
$$2w = \sqrt{L}\sqrt{\frac{8}{\pi}\frac{(1-\nu)G_{crit}}{\mu}}\underbrace{F(k)}_{\approx 1}$$

with Sternlof's data for $2w$ and L,

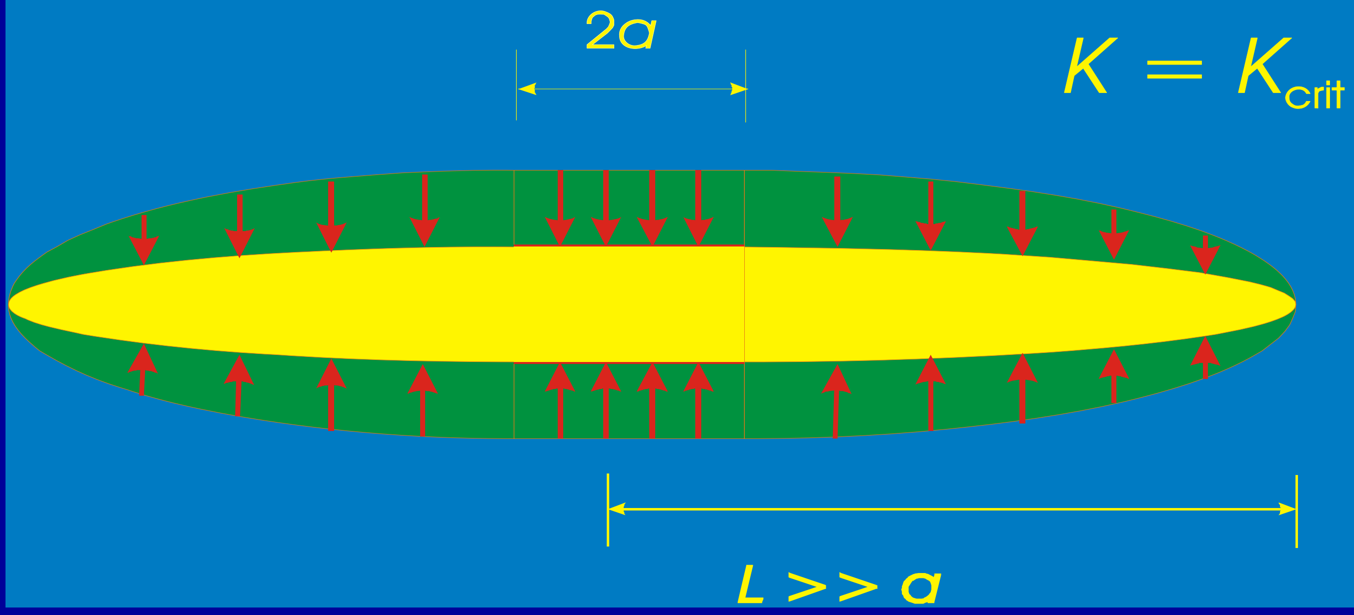
ν=0.2, $\mu = 8.333$ GPa.

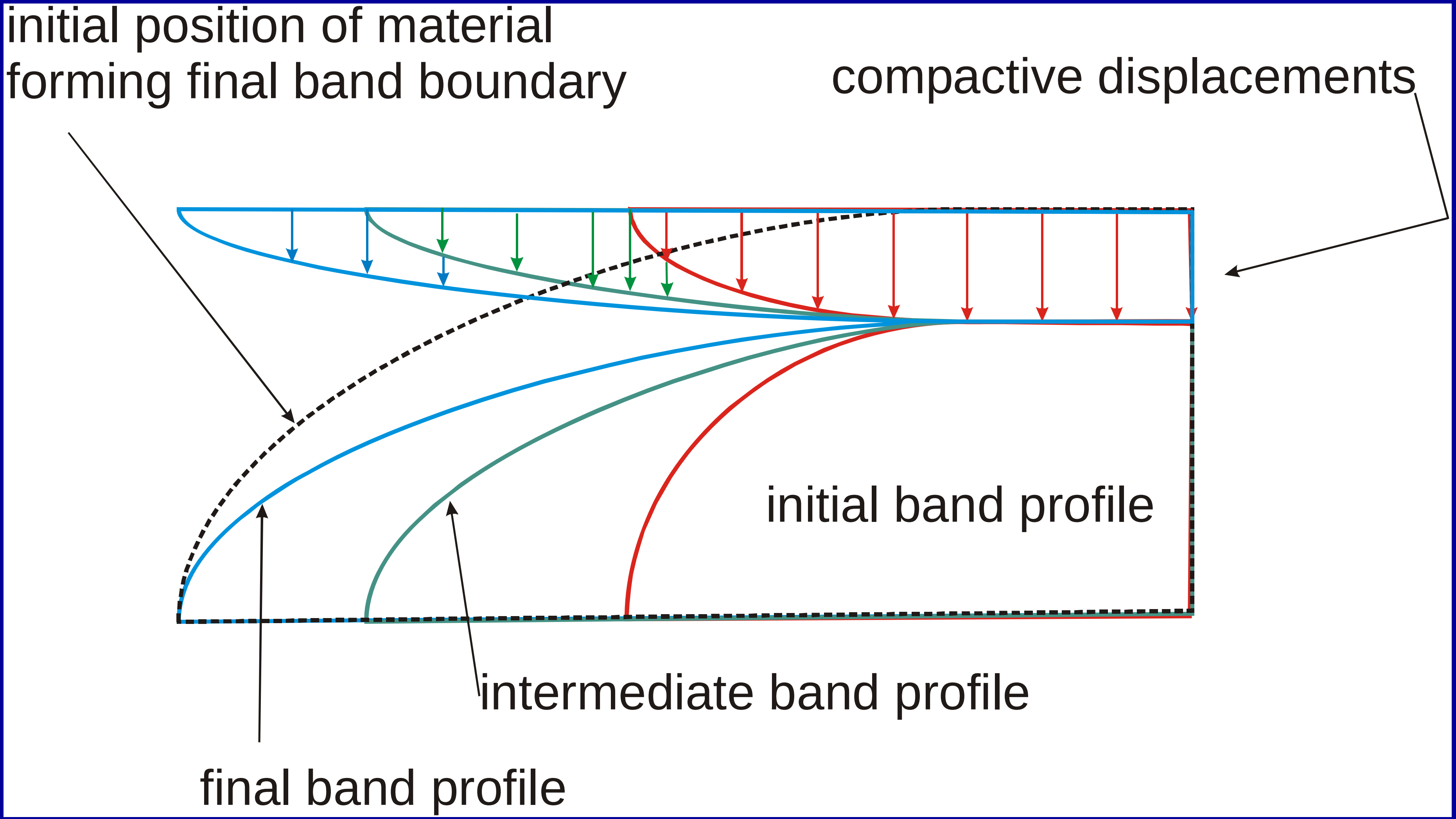


Initial compactive event



Final band length





initial position of material
forming final band boundary
compactive displacements
initial band profile
intermediate band profile
final band profile

Conclusions

- A simple fracture and dislocation model indicates a (surprising) consistency between lab and field data (though multiple interpretations are possible).
- More field and laboratory observations of the breakdown process near the tip of bands would be helpful in constructing more elaborate models.

Thank You!